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APPLICATIONS OF CRYSTAL PLASTICITY IN MULTISCALE MODELING

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ABSTRACT: Multiscale modeling with crystal plasticity constitutive relations is used to determine the average response of a polycrystal. The measured crystallographic texture of a copper shaped charge liner is used in a crystal plasticity model to construct a yield surface that exhibits normal-shear coupling. Simulations with this yield surface model demonstrate the spinning behavior observed in the spin formed copper shaped charges.

INTRODUCTION: Multiscale material modeling offers the promise of being able to determine material properties from simulations or measurements of the microstructure and then representing these effects on material behavior at a larger size scale. One application of this method is in determination of material anisotropy from crystalline orientation distribution functions to calibrate anisotropic yield surfaces used in full scale sheet forming calculations (e.g. Barlat et al [1997]).

The same principals are applied here in the analysis of effects of crystallographic texture on rotation of shaped charge jets using spin formed liners. The focus is on normal-shear coupling in a non-orthotropic material with the determination of constants for the anisotropic yield surface model based on plastic flow direction rather than yield stress

Shaped charges are explosively driven munitions in which a thin-walled hollow cone of a liner material is collapsed to a convergence point. The high pressure at the convergence point causes the liner material to invert and squirt down the axis of the cone at a high velocity. If copper liners are uniaxially back extruded to form the cone, the jet simply shoots down the axis without rotation. If the conical liner is produced by a spin forming operation, the jet also has a superimposed rotation (Winer et al. [1993]).

PROCEDURES, RESULTS AND DISCUSSION: The approach is to use multiscale modeling to determine if the crystallographic texture of the spin formed liner could induce the rotation in the shaped charge jet.

Construction of the Polycrystal Model: A spin-formed copper shaped charge liner was sectioned and the crystallographic orientations over a region of the cross section were measured in a scanning electron microscope using automated indexing of the electron baskscatter diffraction patterns (Schwartz, et al. [2001]). The orientation data from this two dimensional section were used to obtain crystallographic orientations and grain sizes.

The grain size and crystal orientation data were used to construct a finite element model of a representative volume element in which each of the grains was descretized by several elements. The constitutive response was determined using a crystal plasticity model. This accounted for some nonuniform deformation within the grains while satisfying compatibility exactly and equilibrium in an approximate descretized sense. A Taylor model, relaxed constraint model or self-consistent model could also be employed.

Continuum Yield Surface Model: The continuum yield surface was modeled by a generalized quadratic yield function. The form of the yield function and the plastic flow direction determined using assumptions of associated flow and a normality flow rule are:

$$\phi = \sqrt{\sigma'_{ij} K_{ijkl} \sigma'_{kl}} - \bar{\sigma} = 0 \qquad \text{and} \qquad d^p_{ij} = \lambda \frac{\partial \phi}{\partial \sigma_{ij}} = \frac{\lambda}{\bar{\sigma}} K_{ijkl} \sigma'_{kl} \qquad (1)$$

Here σ'_{ij} are the deviatoric components of the Cauchy stress; K_{ijkl} is a matrix of coefficients characterizing the anisotropy in the given reference frame; $\bar{\sigma}$ is the material flow strength measured in a uniaxial test; and λ is the plastic multiplier. Eqn (1b) provides a liner relation for the 21 unknowns of K_{ijkl} in terms of d^p_{ij} and σ'_{ij}.

Determination of Anisotropy Coefficients: The polycrystalline representative volume element is exercised using three isochoric deformations along the three coordinate directions and three pure shear deformations. Each of these six simulations provides six equations for the 21 unknowns of K_{ijkl}. Combining the results from the six simulations gives a system of 36 equations for 21 unknowns. The equations are solved using a singular valued decomposition algorithm that provides a solution in the least squared sense. For this sample, the result is the following symmetric matrix (in Voigt notation):

$$K_{ijkl} = \begin{bmatrix} 0.556 & -0.288 & -0.268 & -0.016 & -0.003 & 0.031 \\ & 0.544 & -0.255 & 0.060 & 0.007 & -0.014 \\ & & 0.523 & -0.044 & 0.004 & -0.017 \\ & & & 0.530 & 0.016 & -0.018 \\ & & & & 0.501 & -0.018 \\ & & & & & 0.512 \end{bmatrix} \qquad (2)$$

Yield Surface Shape: Contours of the plane stress yield surface at different values of in-plane shear show a shift in the center of the elliptical contours as the shear stress increases. The contour shift is the primary effect of interest here. This represents normal-shear coupling where a stress applied along one of the coordinate directions induces a shear strain. This is also evident by examining the matrix in Eqn. (2).

Prediction of Induced Rotation: To determine if the anisotropy computed from the measured crystallographic texture would induce a spin in a configuration similar to that of a shaped charge, a simulation was performed of the collapse of a ring due to suddenly applied external pressure. Fig. 1 shows a twist for the collapsed ring of the anisotropic material but no rotation for when the material is isotropic.

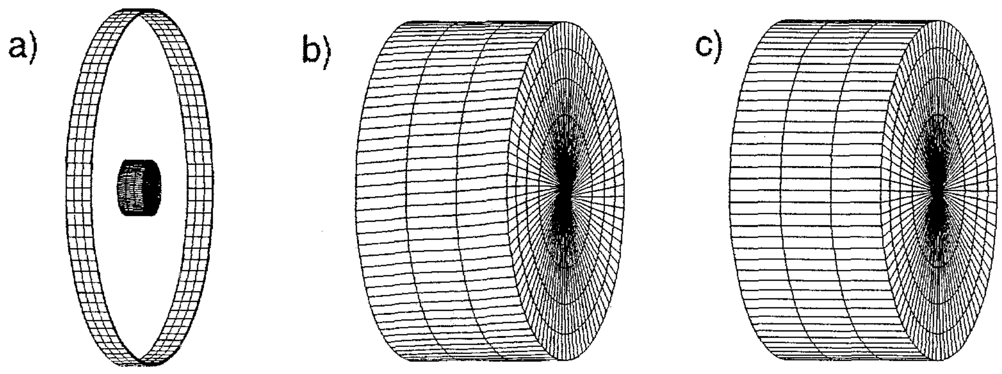

Figure 1. Pressurized ring simulations: a) initial and collapsed ring; b) detail of collapsed ring for anisotropic material; c) detail of ring for isotropic material.

CONCLUSIONS: This work has shown a successful application of multiscale modeling using measured microstructural data to confirm that the crystallographic texture could be a significant cause for the spinning of a shaped charge.

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